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Energy Modeling & Design of Prototype Hydroponic Grow System

An Honors College Project Presented to
the Faculty of the Undergraduate
College of Integrated Science and Technology
James Madison University

by Emily Trawick, Alexander Martin, and
William Stinson

Accepted by the faculty of the Integrated Science and Technology department, James Madison University, in partial fulfillment of the requirements for the Honors College.

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Energy Modeling & Design of Prototype Hydroponic Grow System

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Senior Capstone Project



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Abstract

Energy and food security relies on innovations that spur sustainable ideologies. This project considers a novel approach to grow microgreens within a controlled environment in a manner that conserves water, minimizes environmental impacts from agriculture runoff, and enables successful agriculture in virtually any environment. The eQUEST® software package, an energy simulator, has been used to create a model of the “grow box” considered in this study. The dimensions were specified, and heating, cooling, and other loads were incorporated into the model which was used to estimate energy consumption. Real-time data were collected from sensors installed in the container and were analyzed in Excel and used to validate model performance. The modeling approach allowed for multiple locations to be selected in eQUEST® in order to simulate energy consumption within different climates, and simulations are used to size renewable energy systems and storage in future iterations of the grow box. Potential future applications include military deployments, disaster relief, and urban developments. Grow boxes that completely utilize renewable sources and battery storage will bring these applications to fruition.

1 Introduction

Food--the essential energy source for human survival. Societal structures revolve around food because of its vital importance. The agricultural revolution changed the way humans could live. Instead of spending every day procuring a meal, humans could now focus efforts on other aspects of life. Chasing dreams, not just animals; and cultivating ideas, not just plants. Agriculture has permitted an evolution of the roles in society. People may do what they are passionate about, and not worry every second about having an energy source for survival. Modern cities currently thrive off food grown thousands of miles away. Businesses in the agricultural industry of cultivation, processing, and transportation are flourishing, but only in more affluent areas of the world. Right now, billions of people are starving, CO₂ concentrations are rising, valuable resources are being depleted, and business is going on as usual. Food production plays a major role in the sustainability of current first world norms. Innovations to existing systems are necessary.

Agricultural practices impact the surrounding environment. An increase in need for bigger production per acre has also led to an increase in topical fertilizer use. Topical fertilizers generally runoff during rainfall or irrigation and end up in local waterways, which impacts water quality. These excess nutrients, usually nitrogen and phosphorus, provide a food source for algae and create algal blooms. These algal blooms eventually die and consume dissolved oxygen within the water through the decomposition process, leaving a depletion of oxygen for other aquatic organisms. Agriculture is also a major user of ground and surface water in the United States. As water availability decreases, the cost of water will increase, and with it the production of agriculture. Effective and efficient irrigation and water management practices are vital to running a cost-effective operation. Creating systems that have a closed water cycle and do not continually need to be irrigated will be one solution to remedy the effects from water scarcity.

Hydroponics is the process of growing plants without soil. The goal of a closed system is to create an isolated system where no matter is exchanged with the surroundings. Closed hydroponic systems typically recycle nutrients and water for plant growth. The scope of this topic includes an analysis of a closed hydroponic system through an energy model.

Currently, there are multiple companies who sell closed hydroponic systems. Some of these systems are marketed as “grow boxes” and have a closed hydroponics housed inside of shipping containers. Most companies will ship the containers anywhere in the United States.

Grow box companies create and sell preconstructed hydroponic systems. The companies also provide different system constructions depending on the plants that are desired to be grown. This in turn requires less effort and time from the consumer. These systems are often expensive and smaller companies are unable to keep up timely production when there is an influx of orders. There is a lack of available technology to estimate energy consumption for these current systems in

specific climates. A model of these systems will allow for customers to evaluate approximate energy usage, site renewables, and determine feasibility.

Energy and food security relies on innovations that spur sustainable ideologies. Fidelis Greens has created a closed hydroponic system to grow microgreens year-round. The closed system is used to increase resource utilization and mitigate environmental impacts from agricultural runoff. Fidelis Greens has expertise in agriculture and greenhouse development. However, they lack a background in energy efficiency and modeling. The modeling of this system will allow for future iterations of the grow box to become more energy efficient. Hydroponics allows for the growth of plants without damage to the soil nutrient content, runoff from fertilizers, and more production per unit area.

One question that will be answered with this research is what does a typical energy use profile of a closed hydroponic system in a shipping container in Virginia look like. Problems finding a way to analyze energy efficiency and estimate energy use in various climates for these systems will be addressed.

The purpose of this research project is to create a working energy model of a hydroponic grow system that can be used in future work to further the applicability of hydroponic systems to food production. The objectives of this project include quantification of R-values for the system, collection of energy use from different components in the system, creation of a shipping container model, validation of this model with real-time data, energy efficiency analysis, and preliminary estimation of energy usage for this model in different climates.

It is hypothesized that an energy model will be created and validated with real-time data. This will allow the model to be used as a way to predict energy use for similar systems in different climates. It is also hypothesized that the model can be used to identify places that can increase overall energy efficiency in the system.

To optimize the system, a working energy model of the system is developed, validated with real-time data, and used to determine other viable system locations. The software eQUEST® is used to create a model of the building. Dimensions are specified to the shipping container's length, width, and height, internally and externally. The R-values of the insulation used for container construction are quantified using heat flux and temperature data. Heating, cooling, and electrical loads of all the equipment used during the process are included in the model to better simulate energy consumption. Installed sensors collect real-time energy consumption data, which is analyzed in Excel™ and used to validate the model's energy consumption. Suggestions for increasing energy efficiency are made using the Energy Efficiency Measure (EEM) wizard in eQUEST®. By changing the weather data input to different locations, eQUEST® simulates an accurate load assumption and an estimation of the cost of electricity per month in accordance to the parameters

of that specific location. Once different loads are determined, the viability of using renewable energy sources--solar, wind, and battery storage--based on location may be determined. By having an accurate model, future applications of the system include implementation during military deployments, disaster relief, and permanent use in urban areas.

The remainder of this report includes a literature survey, a detailed outline of hydroponics and the grow box industry, a case study of Fidelis Farm and their project design, and an in-depth look at eQUEST®, the software application used in this project. Project development lists the materials used, the methods, and a results and analysis section. Results and analysis dives into the quantification of inputs for the model produced in eQUEST® along with the validation from real-time energy usage data collected from the system itself. Concluding remarks encompasses a discussion section that evaluates the need for future work. A works cited page of the references used in the development of this project are also incorporated.

“Climate change, water and food security” is a complete analysis of projected climate change and water scarcity influence on food production. This report “summarizes current knowledge of anticipated impacts of climate change on water availability for agriculture and examines the implications for local and national food security” (Turrall, Burke, Faures). It was relied upon to gain a comprehensive understanding of the current global hydrologic cycle and the situation that agricultural production faces. An evaluation of the benefit that closed-system hydroponics could contribute to remedying the problem of water scarcity can be made based on the results concluded in this report.

The United States Department of Energy is the creator of software eQUEST® that we are using throughout our capstone. DOE2.com is where eQUEST® may be downloaded, but also where additional and helpful information may be found about their product. When troubleshooting problems experienced in creating a working model, DOE2.com was the first source turned to solve the problem. There are also user manuals available for eQUEST® on the website that define the meaning of each input parameter that the software prompts for each model creation.

2 Technical & Industrial Aspects

2.1 Grow Boxes

With urban farming and the demand for locally grown produce, a new market has emerged. Several other companies have developed compact, low input systems to satisfy and establish themselves within this new market. The first component of a typical grow box is a container in which to grow and control the climate within. The second component is the growth system in which the plants grow; usually, a hydroponics system which allows water conservation and reduction from soil complications. Lastly, some sort of climate control to optimize plant growth. This also includes the lighting system. Most of the companies tackle this in a similar manner, but differ in their size, scope, specific purpose, relative cost, implemented technologies, and/or level of complexity.

2.2 Hydroponics

Hydroponics is the process of growing plants in sand, gravel, or liquid, with added nutrients but without soil. There are many techniques for hydroponic systems. However, we will focus on a drip recovery system that will use a growing medium from a local Charlottesville company. Substrate, serves as the growth medium in a hydroponic system. Variants of substrate include expanded clay, vermiculite, pumice, gravel, wood fiber, and rice husks. The substrate type depends on the plant being grown.

2.3 Grow Box Components

The purpose of a grow box is to have full control of plant growth variables and for the system to be semi-transportable. For this reason, many companies pick shipping containers for their growth system housing. Shipping containers work well as they are designed for easy maneuverability and adequate space for production inside. The standard shipping container has around 3,000 sq. ft. dependent on internal construction and insulation.



Figure 1: Shipping container used to house the hydroponics growth system at Fidelis Farms.
Photo Credit: Alexander Martin

Installation of the growth platform discerns that capacity and size of plant growth. Nearly every system runs on a hydroponics foundation. This reduces the amount of water needed for growth. Systems differ between companies by either a shelving style system or a vertical hanging system. Pumps are used to circulate the water throughout the system as well as possible filtration systems.

Some systems are outfitted with chemical controls to maintain pH levels and plant available nutrients.

Climate variables within the system are controlled through HVAC for temperature control, dehumidifier for humidity control, and fans for air circulation. LED lighting is utilized and some systems used specific light wavelengths to optimize plant growth. Many of these systems are computer software controlled to minimize human input and improve accuracy. Some of these systems may even be remotely controlled.



Figure 2: Example of a vertical hanging hydroponics growth system. Photo Credit: Freight Farms



Figure 3: Example of a horizontal hydroponics growth system utilizing shallow flow shelving. Photo Credit: Kyle McCrory

There are a variety of lighting options for a hydroponics system. Natural light can be harnessed in a passive system, but this light is not intense and plant remains at its regular pace. For this reason, many developers use energy efficient LED lighting. Compared to traditional incandescent or halogen lighting, LED systems consume less energy as well as produce less heat. This is important because the majority of HVAC operation is spent on cooling the system. Some LED systems have the capacity to apply very specific wavelengths of light to the plants which accelerate growth. The wavelength for optimal photosynthesis lies somewhere between 400 and 700 nm (Tenningas, 2013). This is a very specific wavelength when compared to the 290 to 3,200 nm span of natural light (The Sun, n.d.). This provides the plant with only the light necessary for growth and increases production. Another benefit of LED lighting is the ability to continue applying light well past the natural schedule of the sun. This means systems can have periods of “daylight” extending from the average natural length of 12 hours to upwards of 16 to 20 hours of light a day. The extension of light exposure drastically increases plant productivity.

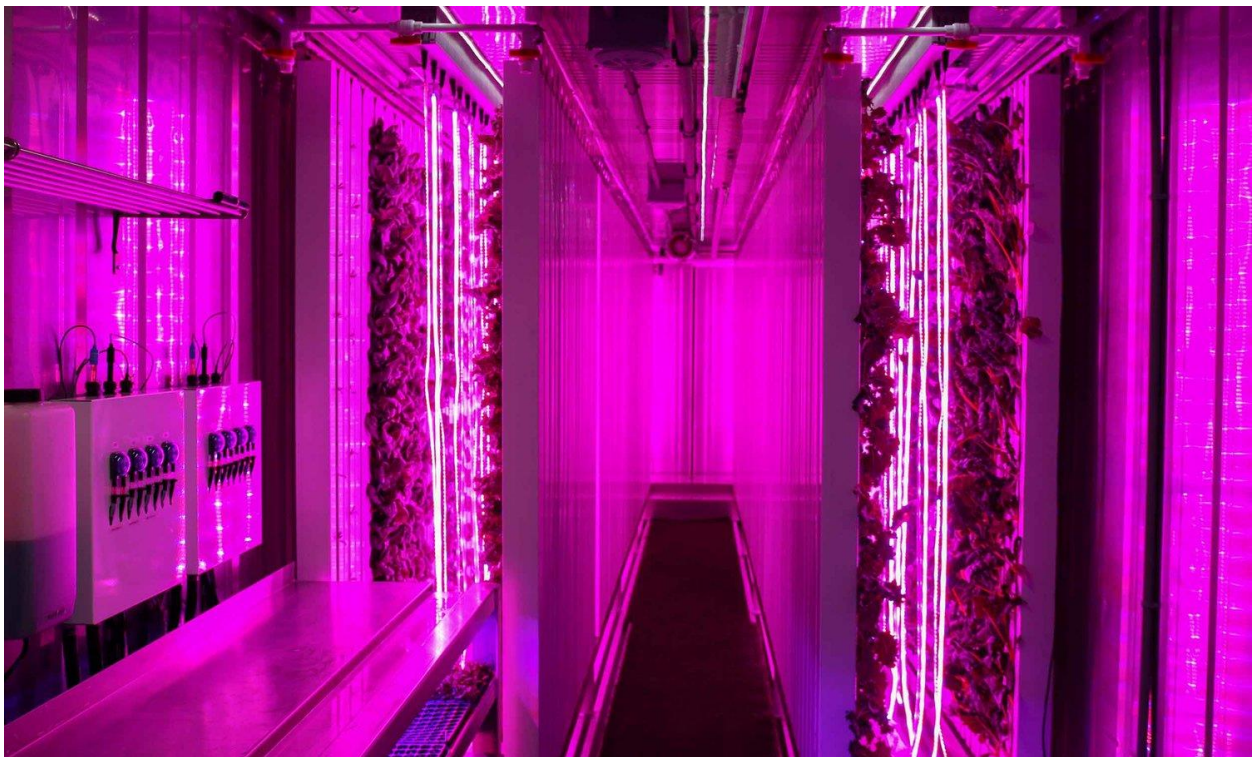


Figure 4: Wavelength specific for growth LED lighting utilized in a vertical system. Photo Credit: Freight Farms

Many new hydroponic growth systems are moving towards a fully integrated computer control system, some of which can be remotely accessed and controlled. The computer gathers data through a variety of sensors measuring variables such as temperature, humidity, water pH, CO₂ levels, and other inputs. The computer can then control systems such as the HVAC system to control temperature and CO₂ levels, dehumidifier to control humidity, and chemical balancers for water pH levels.



Figure 5: *The computer control system utilized at Fidelis Farms to control system variables. Photo Credit: Alexander Martin*

2.4 Grow Box Competitors

Multiple companies are capitalizing on the opportunity to develop a compact growth system for commercial sale. Companies have varied approaches to the technologies utilized within their systems.

Square Roots

Utilizing a completely vertical grow system, Square Roots can grow higher quantities in a smaller space. Paired with lighting specific to exciting plant growth, the company is able to produce more than 50 lbs. of produce a week in a single shipping container while only consuming about 8 gallons of water a day. The educational campus, which focuses on teaching entrepreneurs the farming and business aspects of the industry, runs multiple grow boxes on their campus in Brooklyn, NY.



Figure 6: Shipping container utilized by Square Roots with vertical hydroponics.

Agrinamics

Growth in Agrinamics containers follows the more traditional vertical growing via a shelving system. The company utilizes a completely integrated software system in order to control the climate within the containers. Where Agrinamics separates itself from the competitors is by creating larger scale operations by combining multiple grow boxes into one system.



Figure 7: An example of Agrinamics modular combination system to create larger growth spaces.

CropBox

Using the shelving style vertical hydroponics growth system, CropBox is capable of growing the equivalent of an acre of conventional farmland in single container unit. The system is also capable of being stacked 5 units high in order to conserve space and increase production. Using a software monitoring system, the internal climate is completely controllable.



Figure 8: Cropbox's horizontal hydroponic shelving and shipping container layout.

Freight Farms

Freight Farms grow boxes use a completely vertical grow system with detachable hanging units for easy planting, harvesting and moving. The hanging system, similar to square roots, allows for more production within the limited space. The grow box also uses software to completely control the climate as well as the soil nutrients of the system. As one of the costlier units, Freight Farms produces a well-polished system with all the technological implementations to stand out among their competitors.



Figure 9: Freight farms compact vertical hanging hydroponics system utilizing wavelength specific LED growth lighting in their marketed shipping container.

Modular Farms

Modular farms allow their consumers to expand after purchasing by developing a modular system which allows for easy additions. They utilize a completely vertical hanging growth system with wavelength specific growth lighting. The company also produces smaller containers for specific tasks such as energy production, water collection, storage, plant nurseries. This allows for full customization by the customer to fit their needs.



Figure 10: *Modular farms vertical hanging hydroponics system utilizing wavelength specific LED growth lighting in their marketed container which offers more space than the typical shipping container system.*

3 Fidelis Farm

3.1 Fidelis Farm & Technologies

Fidelis Farm & Technologies, the parent company of Fidelis Greens, was founded in Crozet Virginia. Fidelis Farm & Technologies sets itself up as a business start-up developer with the purpose of improving the technology and systems which affect efficiency and sustainability of farms and vineyards. Mr. Randy Caldejon, founder, executes the role of team leader and helps lead his team of innovators in developing these technologies. Mr. Caldejon's team is primarily composed of former members of U.S. armed forces with himself having served with the U.S. Marine Corps. Second in command at the farm is Mr. Andre Ortiz who also served with the U.S. Marine corps and manages systems at the farm. Other members of the Fidelis Farm team include Mr. Kyle McCrory who focuses on industrial design and horticulture, and Mr. Joel Shindeldecker who focuses on client accounts and marketing aspects of the company.

3.2 Fidelis Greens

Fidelis Greens has developed a hydroponic grow box made from an upcycled shipping container. To mitigate the environmental impacts from agriculture runoff and optimize water usage their

design focuses on growing food for a local consumer within a closed system. Fidelis Greens aims to conquer the variables that traditional agriculturalists fight against in the production of their crops that limit total production output and the growing season. The best way to do that is to enclose the system and implement a full range of sensors and systems to control the remaining variables in the growth of the crop. One of Fidelis's first major agricultural successes was in the form of implementing a sensor network across the 16-acre vineyard located at the farm. These sensors help keep track of growing conditions across the system to better aid the farmers growing the crop and to be more efficient in the upkeep of the crop. The reason behind this is so that local chefs can have a high quality, local product, year-round with relatively no inconsistencies between deliveries (Stafford, 2017).

3.3 Motivation & Future Goals

This project was originally motivated by a desire to venture into a new market. Mr. Caldejon is a businessman who is always looking for the next investment and he wanted to provide microgreens for the local Charlottesville area year-round. He researched a few companies that could provide hydroponic containers, but always ran into a problem with the cost or the company itself. The creation of Fidelis Farm's own hydroponic shipping container was then born. A main goal for future iterations of these boxes is to develop a self-sustaining box that does not rely on grid power. As a military man, Mr. Caldejon immediately thought that these boxes could have a military application if they were mobile and off the grid. With possible military aid as a driving incentive for this project, it became a reality.

3.4 Project Design

The 40 ft standard steel shipping container was converted into a hydroponic greenhouse with a few changes. A door that people could easily enter and exit out of was added on one of the 40 ft sides. Once the door frame was cut out and the door was installed, the floors needed to be finished. The floor was created using R3 1/2-inch foam that was glued to the existing steel bottom using liquid nails adhesive. In between each foam board there is a weather seal tape as an added barrier. 4.25 inches was cut off each 4' x 8' OSB sheet and applied on top with T-20-star bit deck screws that are corrosion resistant. A "UCoat It" floor epoxy kit was used to create the final flooring. The internal walls were created using moisture and mold resistant drywall. There was a gap left between the drywall and the steel container, to add the spray foam insulation. A ceiling with overhead lighting was also added, but is never used because the task lighting provides enough light to work with. Three water troughs to hold the water for the plants and a pump were installed below where the plants will grow. There are 6 vertical racks that serve as shelving units. There is a total of 6 ebb and flow tables on each vertical shelf, which allow water to flow in and drain out. An infinity LED lighting system was attached to the bottom of each shelving units to serve as task lighting for the plants. The HVAC and electrical components reside on the end of the shipping container that has the door. The HVAC could not circulate throughout the length of the container very well. As a result, small fans were installed to help circulate the air. A vent on the top of the

ceiling was also added to carry some of the air from the HVAC system at the front of the box to the back of the box. The sealable “door” that originally served as the door to the shipping container was sealed off and is no longer functional. It was sprayed with insulating spray foam, but does not have drywall placed on this panel of the container. The final step in the creation of the hydroponics container includes painting the outside white.

4 eQUEST®

The software eQUEST® is a building and HVAC energy modeling tool widely accepted in the field. It is a free analysis tool provided by the Department of Energy (DOE) to help budget and design buildings. (Wang, Lieu, and Gates, 2015) The hydroponic system, although smaller than the typical eQUEST® project, could utilize much of the eQUEST® tool. Dimensions of the container were specified to the shipping container’s length, width, and height. Heating, cooling, electric loads, and many other aspects of the system were added to the model to simulate energy consumption.

eQUEST® is a software that was developed by James K. Hirsch and Associates for the U.S. DOE to create basic to advanced building models. It is an advanced design tool that is also easy-to-use, making it the perfect tool to simulate the hydroponic system. eQUEST® stands for “the Quick Energy Simulation Tool,” and through its use it has been determined it is an accurate name for this software. (DOE2.com) Models are created to exact specifications of the desired design. Specifications include building square footage, orientation, local weather data, power loads, HVAC equipment, and much more. By combining all these factors in one design tool, one may get a more accurate estimation of power consumption and loads.

A wide variety of buildings may be modeled using eQUEST®. It may vary from small residential homes, under 1,000 ft², to large industrial parks, over 20,000 ft². eQUEST® generates both two dimensional and three-dimensional renditions of the building. Almost every detail of the building may be customized, from the color of walls to the placement of a window, as precise as a tenth of an inch. An example may be seen in **Figure 11** below. Materials may also be specified in and outside of the house. Specifications, such as this, allows the user to choose materials which represent thermodynamic properties of the building. These properties are extremely impactful on the load profile.

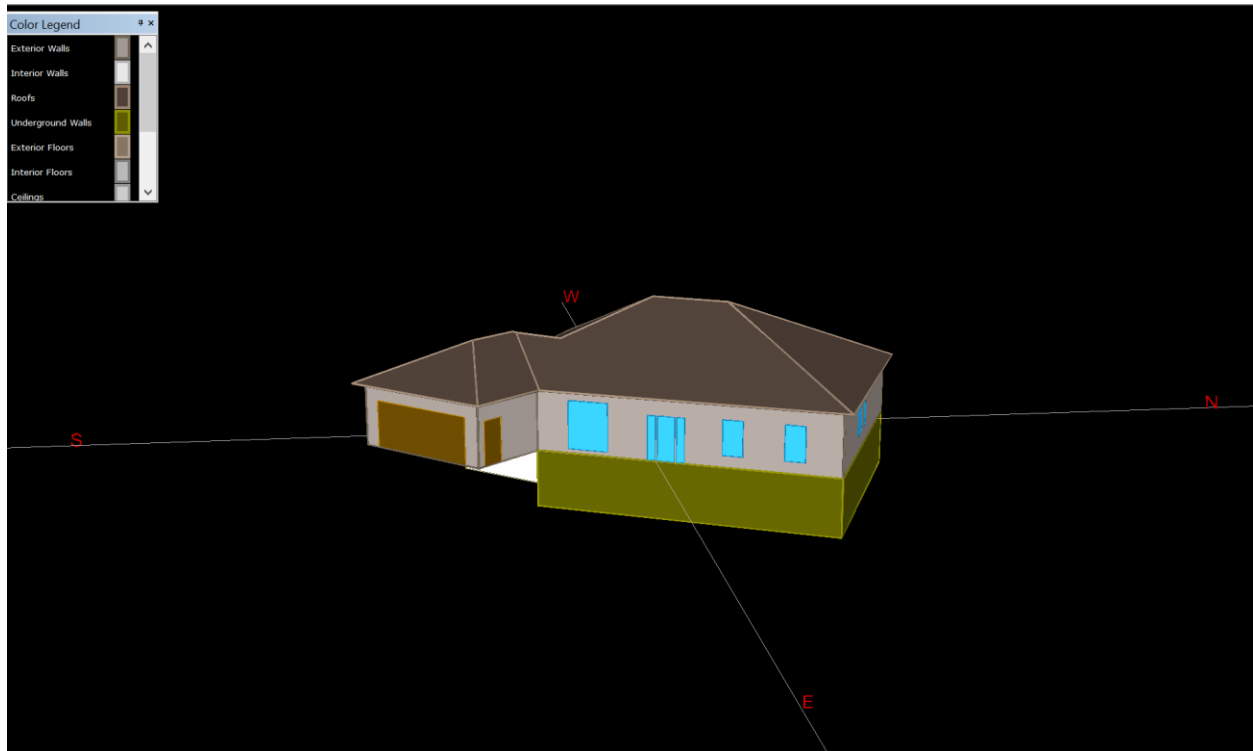


Figure 11: A model of a residential building. eQUEST® allows the specification of door and window placement down to a tenth of an inch. This placement, along with orientation of the house is used to determine passive heating of the house by the sun. It also allows for the user to select different materials for different parts of the house and draw exact layouts.

Even with a large variety of inputs, eQUEST® can run a simulation in under a minute. This is faster than other software's on the market with similar complexities. Of course, run-time can vary depending on the complexity of the model. In the case of a residential building, the under-one-minute rule still applies. For large, multi-shell buildings, a longer runtime should be expected.

Once a simulation has been run, a variety of reports are now at the user's disposal. A full list of available reports can be seen in **Figure 12** below.

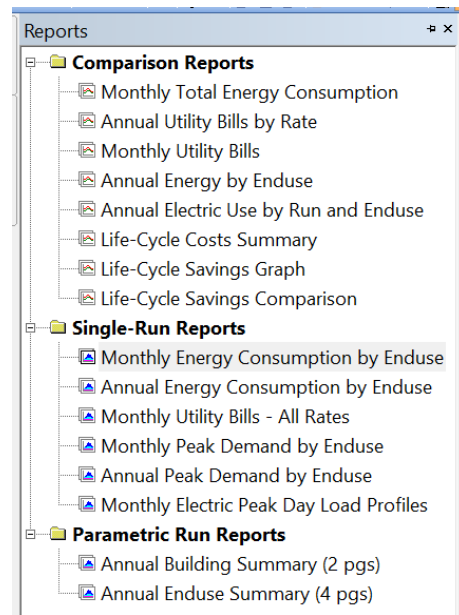
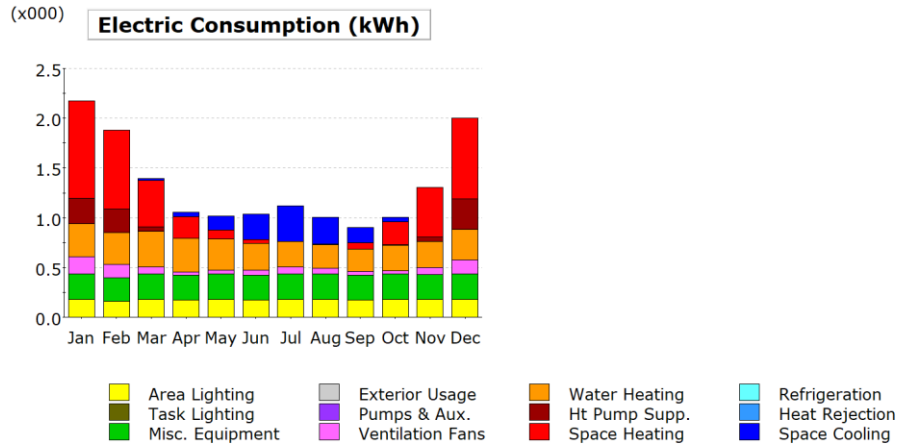


Figure 12: *There is a wide range of reports available for the user. Comparison reports allow the user to optimize energy efficiency techniques, single-run reports allow the user to see the results of their model, and parametric reports are used to compare different models.*

Reports may be broken up annual to monthly and show energy consumption or predicted utility rate. Single-run reports may be utilized after the first run of the software. These reports have simulated data about the performance of the building based on the previous inputs. An example of a report is in **Figure 13** below. Comparison reports become important after modifications have been made to the model in the Energy Efficiency Measure (EEM) Wizard have been made. Side-to-side comparisons are shown, so the user may determine the impact that a EEM modification may have. Lastly, parametric run reports are useful when comparing completely different models to determine which is the best design.



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.02	0.04	0.14	0.26	0.36	0.27	0.15	0.05	0.00	-	1.28
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.98	0.79	0.47	0.22	0.09	0.03	0.00	0.00	0.06	0.23	0.50	0.81	4.18
HP Supp.	0.25	0.24	0.05	0.00	0.00	-	-	-	-	0.01	0.05	0.31	0.90
Hot Water	0.34	0.32	0.36	0.34	0.31	0.27	0.25	0.24	0.23	0.25	0.26	0.31	3.48
Vent. Fans	0.17	0.14	0.07	0.03	0.03	0.05	0.07	0.05	0.04	0.03	0.07	0.14	0.89
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.26	0.23	0.26	0.25	0.26	0.25	0.26	0.26	0.25	0.26	0.25	0.26	3.03
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.18	0.16	0.18	0.17	0.18	0.17	0.18	0.18	0.17	0.18	0.18	0.18	2.12
Total	2.18	1.88	1.39	1.05	1.02	1.03	1.12	1.00	0.90	1.00	1.30	2.00	15.88

Figure 13: A monthly energy consumptions by end-use report of a residential building. The report breaks down the results of different end-uses (i.e. heat pump supply, area lights, or miscellaneous equipment) by month both graphically and in table form.

eQUEST® is a powerful tool with the ability to fully model complicated industrial scale buildings. All the power of eQUEST® will be utilized for this report. However, it does set the stage for future analysis to be done on the system as the product becomes finalized and its usage becomes clearer. In this report, the main usage of eQUEST® was to acquire accurate load data, and to place the model in different environments to determine the energy demand.

5 Project Development

The purpose of this project is the create a working energy model of a hydroponic grow system. Future applications of this model include siting and sizing of renewables and deployment feasibility studies for urban developments, military applications, or disaster relief.

5.1 Materials

5.11 Standard Shipping Container

A standard shipping container serves as the environment for growing the hydroponic system. The containers are made of steel and are 40 ft long, 8.5 ft high, and 8 ft wide. Insulation with an R-value of about 7 per inch is sprayed 2 inches thick around the walls and ceiling of the container. Then walls are placed 3 inches inside the container on each side to provide scaffolding for the

shelves, HVAC units, control panel, and other necessary hardware. The inside of the unfinished hydroponic system is shown in **Figure 14** below.



***Figure 14:** The figure above shows the first iteration of the shipping container used to gather data.*

5.12 Hydroponic Pump

The hydroponic pump is equipped with insulated and heated housing on the outside. This is a precautionary method to avoid freezing pipes in the winter. Water is pumped from large basins seen in the bottom of **Figure 14** to the top of the system. It is then brought down by gravity to each of the six selves. The pump used is a Sta-Rite P6E6C-204L Max-E-Pro which rated at ½ HP and 115 volts.

5.13 HVAC

The heating and cooling system is a mini-split unit. Which means that it has both an air exchanger on the inside and the outside of the unit and it exchanges air only from a 3-inch diameter pipe running between the inside and outside of the shipping container. The unit may be seen on the upper right side of the container.

5.14 Microgreens

Microgreens will serve as the crop grown due to their quick growing period. From germination to harvest, microgreens take about a month to grow. The greens may be used as a supplemental food for salads, sandwiches, soups, and so on. Of all infant seed plants, they have some of the highest recorded nutrient values. An example of these crops is shown in **Figure 15** below. Due to their quick growing period, one may see how they react to different stimuli faster than other crops. This project will specifically focus on microgreens as a crop.



Figure 15: *The figure above shows the original prototype hydroponic system with its first round of microgreens growing.*

5.15 Heat Flux Plate

The Hukseflux® HFP01 heat flux plate is a heat flux sensor that will be utilized in the project to collect data about heat transfer in and out of the hydroponic system. These sensors read the amount of heat transfer per unit area and have an output reading in voltage. The Hukseflux website gives specifications for the range of heat transfer and temperature that these sensors can be used for. This application falls within the specified range. The sensitivity of the sensor is given as $60 \mu\text{V}/(\text{W}/\text{m})^2$ and is used to convert the electric signal from $\mu\text{V}/(\text{W}/\text{m})^2$ to $\text{Btu}/\text{hr}\cdot\text{ft}^2$.

5.16 Temperature Sensors

The temperature sensors used are Type-T Thermocouple wires manufactured by Omega®. These sensors are made of a copper-nickel combination and have a sensitivity of $43\mu\text{V}/^\circ\text{C}$. The thermocouples will measure the indoor and outdoor air temperature as well as the indoor and outdoor surface temperature of a wall, the door, and the ceiling for the hydroponics system.

5.17 Data Loggers

Omega® DaqPro 5300 is a portable handheld data logger that will be equipped inside with the heat flux and temperature sensors. The DaqPro 5300 able to store a large amount of data and multiple logging sessions. USB-603 is a two-channel thermocouple logger made by Measurement Computing that will be equipped outside with temperature sensors. This thermocouple logger is battery powered and able to store over 250,000 readings. The data will be imported from both data loggers into Excel® for analysis.

5.18 Excel

Excel® is an application software provided in the Microsoft office suite of applications. This software allows for data analytics and visual data representation generation. It will be used to analyze the heat flux and temperature data collected by the data loggers and calculate the R-value for multiple components of the hydroponic system.

5.2 Methods

5.21 Data Acquisition

Real time hourly data was collected from the sensors that have been installed in the container for accurate input values into the eQUEST® model. The data necessary for the completion of the model includes interior and exterior surface temperature values, indoor and outdoor temperature values, heat flux values, and electrical load values. Temperature values and heat flux values were collected using thermocouples and a heat flux sensor over a two-day period. These values were then used to calculate the R-value of the walls, door, and the ceiling. Electrical load values were collected based off equipment specification information provided by the manufacturer. Electrical loads were procured for the water pump, lighting system, and HVAC system. Sensors which have been installed measure indoor and outdoor air temperature, energy usage, and humidity. This data was analyzed in Excel and used to validate the model loads. Total energy consumption per hour for each load type was then calculated.

5.22 Environment Simulation

Since the model has been validated from real-time data, the model was simulated in eQUEST® again in different environments. The environments chosen were Florida and North Dakota. These are places that the system has the potential to be implemented with solar or wind power as the only provision of power for the system.

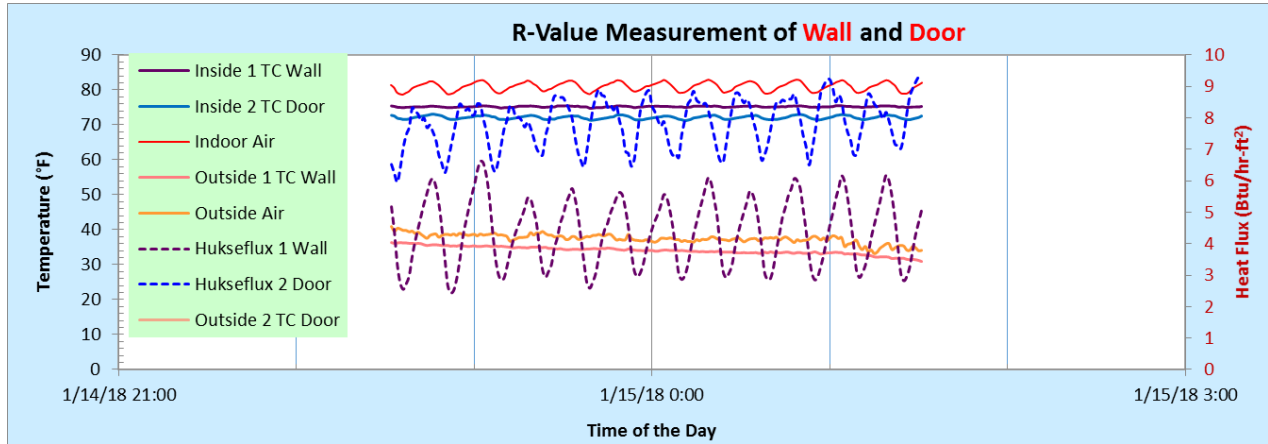
5.3 Model Input Analysis

The model inputs analyzed include NREL weather data, insulation values, lighting, internal loads, HVAC systems, and model footprint. The following section specifies how these inputs were determined.

5.31 R-value Calculation

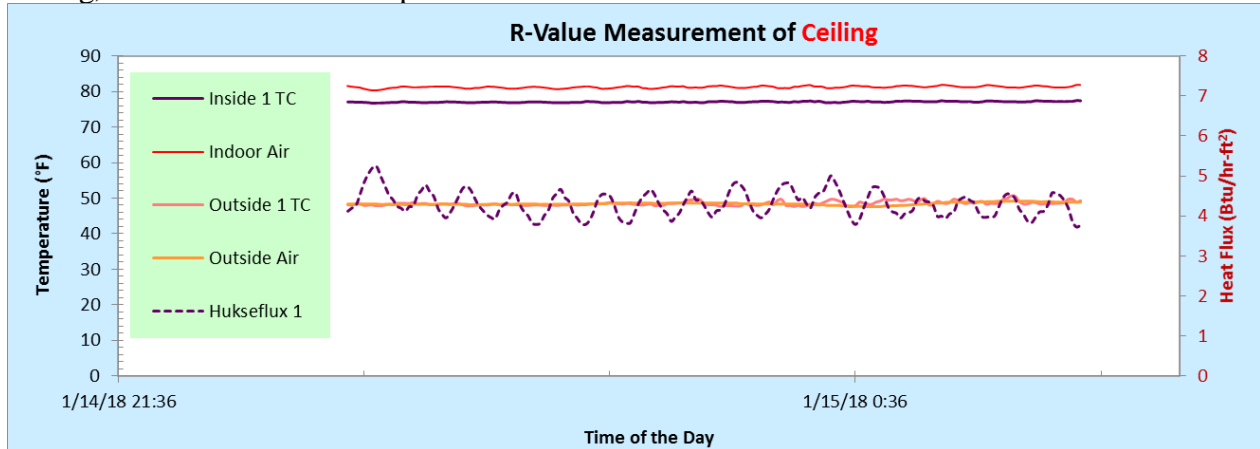
Proper insulation values are essential to building a working model in eQUEST®. The R-values for three components of the system were analyzed: the wall, the door, and the ceiling.

The data set logged for the wall, the door, and the ceiling was reduced to a 3-hour steady state period chosen from all the data collected. This allows for an easier analysis as well as a more accurate evaluation of the R-value for each component. The data collected for the wall and the door between 10:26 pm on February 9th, 2018 and 1:25 am on February 10th, 2018 are shown below in **Graph 1**. The inside surface temperatures for the wall and the door, inside air temperature, heat flux output for the wall and the door, the outside surface temperatures for the wall and the door, and the outside air temperature are shown.



Graph 1: The graph above shows the temperature and heat flux data from 10:26 pm on February 9th, 2018 to 1:25 am on February 10th, 2018 for a wall and the door of the shipping container in Crozet, VA.

The data collected for the ceiling between 9:43 pm on February 10th, 2018 and 12:42 am on February 11th, 2018 are shown below in **Graph 2**. The inside surface temperatures for the ceiling, inside air temperature, heat flux output for the ceiling, the outside surface temperatures for the ceiling, and the outside air temperature are shown.



Graph 2: The graph above shows the temperature and heat flux data from 9:43 pm on February 10th, 2018 to 12:42 am on February 11th, 2018 for the ceiling of the shipping container in Crozet, VA.

R-value is calculated using the following equation,

$$R \equiv \frac{\sum T_h - \sum T_c}{\sum \dot{q}} \quad (1)$$

Where R is the measured R-value, T_h is the warm surface temperature in, T_c is the cold surface temperature, and \dot{q} is heat flux.

The summation values for the wall of T_h was found to be 14,571 °F, of T_c was found to be 6,738 °F, and of \dot{q} was found to be $785 \frac{Btu}{hr-ft^2}$. By substituting these values into Equation 1, as shown below, the measured R-value can be found.

$$R = \frac{(14,571 - 6,738)^{\circ}\text{F}}{785 \frac{\text{Btu}}{\text{hr} - \text{ft}^2}}$$

$$R = 9.98 \frac{\text{hr} - \text{ft}^2 - ^{\circ}\text{F}}{\text{Btu}}$$

This same approach was used to find the measured R-values for the door and the ceiling. These values are shown below in **Table 1**.

Table 1: The table below shows the measured R-values for a wall, the door, and a ceiling in a hydroponic shipping container in Crozet, VA.

	R-Value (hr-ft ² -°F/Btu)
Wall	9.98
Door	5.55
Ceiling	7.60

These measured R-values do not take the conductive and convective heat transfer into account.

As a result, the final values will be calibrated using the following equation,

$$R_{calibrated} = (R * 0.903) + 0.4972 \quad (2)$$

Where $R_{calibrated}$ is the calibrated and accepted R-value in $\frac{\text{hr} - \text{ft}^2 - ^{\circ}\text{F}}{\text{Btu}}$ and R is the measured R-value in $\frac{\text{hr} - \text{ft}^2 - ^{\circ}\text{F}}{\text{Btu}}$.

The following substitution is made to calculate the calibrated R-value for the wall.

$$R_{calibrated} = \left(9.98 \frac{\text{hr} - \text{ft}^2 - ^{\circ}\text{F}}{\text{Btu}} * 0.903 \right) + 0.4972$$

$$R_{calibrated} = 9.51 \frac{\text{hr} - \text{ft}^2 - ^{\circ}\text{F}}{\text{Btu}}$$

The same approach was used to determine the final calibrated R-value for the door and the ceiling. These values can be found in Table 2.

Table 2: The table below shows the calibrated R-values for a wall, the door, and the ceiling in a hydroponic shipping container in Crozet, VA.

	R-Value (hr-ft ² -°F/Btu)
Wall	9.51
Door	5.13
Ceiling	7.36

To find the total uncertainty associated with the R-value measurement, the uncertainty of each measurement used to calculate the R-value must be found. The following equation is used to determine the uncertainty of the entire sample of surface temperature measurements,

$$\Delta(\sum T) = \sqrt{n(\Delta T_i)^2} \quad (2)$$

Where, $\Delta(\sum T)$ is the uncertainty of the summation of the surface temperature measurements, n is number of samples, and ΔT_i is the uncertainty for each sample.

With a total number of samples of 180 and an assumed uncertainty of 0.5 °F for each sample, the following substitutions are made to solve for uncertainty of the entire sample population,

$$\Delta\left(\sum T\right) = \sqrt{180 * (0.5\text{ }^{\circ}\text{F})^2}$$

$$\Delta\left(\sum T\right) = \pm 6.7\text{ }^{\circ}\text{F}$$

This uncertainty can be applied to surface temperature measurements for the warm and cold surface temperature for the wall, the door, and the ceiling.

The following equation is used to determine uncertainty of the measurement for the total amount of heat flux,

$$\Delta(\sum \dot{q}) = \Delta\sqrt{\sum(\dot{q}_i)^2} \quad (3)$$

Where, $\Delta(\sum \dot{q})$ is the uncertainty of the summation of the heat flux measurements and $\sum(\dot{q}_i)^2$ is the summation of the individual heat flux measurements.

The manufacturer has a calibration uncertainty of $\pm 3\%$ equally distributed for the Hukseflux HFP01 heat flux plate. The summation of each heat flux measurement is 785 Btu/hr-ft² for the wall. The following substitution is made to calculate the uncertainty of the total amount of heat flux for the wall,

$$\Delta\left(\sum \dot{q}\right) = 0.03 \sqrt{\sum \left(785 \frac{\text{Btu}}{\text{hr-ft}^2}\right)^2}$$

$$\Delta\left(\sum \dot{q}\right) = \pm 1.8 \frac{\text{Btu}}{\text{hr-ft}^2}$$

This value represents the uncertainty associated with the total amount of heat flux for the wall.

The same calculations were performed for the door and the ceiling. The uncertainty for the total amount of heat flux for the door is $\pm 3.2 \frac{\text{Btu}}{\text{hr-ft}^2}$ and the ceiling is $\pm 1.7 \frac{\text{Btu}}{\text{hr-ft}^2}$.

The following equation is used to determine uncertainty of the measured R-value,

$$\Delta R = \sqrt{\left(\Delta T_h \frac{\partial R}{\partial T_h}\right)^2 + \left(\Delta T_c \frac{\partial R}{\partial T_c}\right)^2 + \left(\Delta \dot{q} \frac{\partial R}{\partial \dot{q}}\right)^2} \quad (4)$$

Where ΔR is the uncertainty of the uncalibrated R-value, ΔT_h is the uncertainty of the warm surface temperature, $\frac{\partial R}{\partial T_h}$ is the partial derivative of the R value with respect to the warm surface temperature, ΔT_c is the uncertainty of the cold surface temperature, $\frac{\partial R}{\partial T_c}$ is the partial derivative of the R-value with respect to the cold surface temperature, $\Delta \dot{q}$ is the uncertainty of the total amount of heat flux, and $\frac{\partial R}{\partial \dot{q}}$ is the partial derivative of the R value with respect to heat flux.

The partial derivative of R with respect to T_h can be found by referencing Equation 1 and is as follows,

$$\frac{\partial R}{\partial T_h} = \frac{1}{\dot{q}} \quad (5)$$

Where, $\frac{\partial R}{\partial T_h}$ is the partial derivative of the R value with respect to the warm surface temperature and \dot{q} is the total of heat flux.

The following substitution can be made to solve for the warm surface temperature partial derivative value of the wall,

$$\frac{\partial R}{\partial T_h} = \frac{1}{785 \frac{Btu}{hr - ft^2}}$$

$$\frac{\partial R}{\partial T_h} = 0.00127 \frac{hr - ft^2}{Btu}$$

The partial derivative of R with respect to T_c can be found by referencing Equation 1 and is as follows,

$$\frac{\partial R}{\partial T_c} = -\frac{1}{\dot{q}} \quad (6)$$

Where $\frac{\partial R}{\partial T_c}$ is the partial derivative of the R value with respect to the cold surface temperature and \dot{q} is the total of heat flux.

The following substitution can be made to solve for the cold surface temperature partial derivative value of the wall,

$$\frac{\partial R}{\partial T_c} = -\frac{1}{785 \frac{Btu}{hr - ft^2}}$$

$$\frac{\partial R}{\partial T_h} = -0.00127 \frac{hr - ft^2}{Btu}$$

The partial derivative of R with respect to \dot{q} can be found by referencing Equation 1 and is as follows,

$$\frac{\partial R}{\partial \dot{q}} = -\frac{T_h - T_c}{\dot{q}^2} \quad (7)$$

Where $\frac{\partial R}{\partial \dot{q}}$ is the partial derivative of the R value with respect to the total heat flux, T_h is total warm surface temperature, T_c is total cold surface temperature and \dot{q} is the total of heat flux.

The following substitution can be made to solve for the heat flux partial derivative value of the wall,

$$\frac{\partial R}{\partial \dot{q}} = -\frac{(13559 - 6152)^\circ F}{(785 \frac{Btu}{hr - ft^2})^2}$$

$$\frac{\partial R}{\partial \dot{q}} = -0.01201 \frac{(hr - ft^2)^2 - ^\circ F}{Btu^2}$$

The values found for each partial derivative can be substituted into Equation 4 to solve for the uncertainty of the measured R-value. That substitution is as follows,

$$\Delta R = \sqrt{\left(\left(6.7^\circ F * 0.00127 \frac{hr - ft^2}{Btu} \right)^2 + \left(6.7^\circ F * \left(-0.00127 \frac{hr - ft^2}{Btu} \right) \right)^2 \right.}$$

$$\left. + \left(1.8 \frac{Btu}{hr - ft^2} * \left(-0.01201 \frac{(hr - ft^2)^2 - ^\circ F}{Btu^2} \right) \right)^2 \right.}$$

$$\Delta R = \pm 0.0249 \frac{hr - ft^2 - ^\circ F}{Btu}$$

These calculations were repeated for the uncertainty analysis of the door and the ceiling as well. The calibrated R-values with their associated uncertainty can be found in **Table 3** below.

Table 3: The table below shows the calibrated R-values and their associated uncertainty for a wall, the door, and the ceiling of a hydroponics system housed in a shipping container in Crozet, VA.

	R-Value (hr-ft ² -°F/Btu)
Wall	9.51 ± 0.02
Door	5.13 ± 0.01
Ceiling	7.36 ± 0.02

5.32 Modeling the System in eQUEST®

A model of the shipping container was created in eQUEST® using the Building Creation Wizard. The system, due to its unique shape and usage compared to typical commercial buildings, had to be created as a custom-building type. To begin crafting the model, the location must first be input. Crozet was not a possible choice, so Charlottesville, the closest town with available weather data, was chosen. Charlottesville is 19 miles away from Crozet, so it may be assumed that they experience very similar weather on average throughout the year.

A custom building demands a custom footprint design and orientation. The orientation of a building is typically very important to energy demand when considering passive efficiency design. Since the system does not have any windows, the orientation most likely had little impact on the outputs. However, the orientation of the model was still input as close to the real system as possible and can be seen below in **Figure 16**.

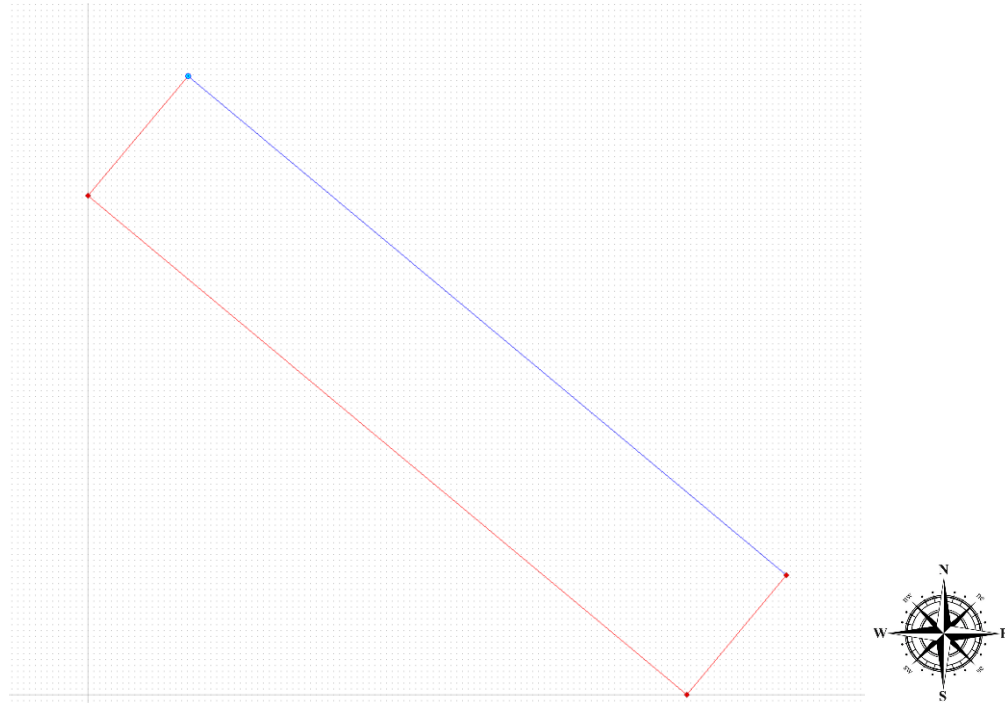


Figure 16: The orientation and basic footprint of the building. The orientation was determined by using google maps while basic trigonometry was used to determine the point of each location.

Once orientation was set, the building envelope could be created. Specifics about the building are entered through drop down menus in the building wizard. Materials for the roof, walls and floor was selected. Exact materials, such as galvanized steel could be selected for each part of the envelope. Additionally, the predetermined R-values of the walls, ceiling, and floor were all input into this section, **Figure 17** shows the specifics of each input.

The screenshot shows a software interface titled "Building Envelope Constructions". It is divided into three main sections: "Roof Surfaces", "Above Grade Walls", and "Ground Floor".

- Roof Surfaces:**
 - Construction: Metal Frame, > 24 in. o.c.
 - Ext Finish / Color: Steel, galvanized (wea) | White, lacque
 - Exterior Insulation: - no ext board insulation -
 - Add'l Insulation: R-7 batt, no rad barrier
 - Interior Insulation:
- Above Grade Walls:**
 - Construction: Metal Frame, 2x6, 24 in. o.c.
 - Ext Finish / Color: Steel, galvanized (wea) | White, lacque
 - Exterior Insulation: 3/4in. fiber bd sheathing (R-2)
 - Add'l Insulation: - no batt -
 - Interior Insulation: 1 in. polyisocyanurate (R-7)
- Ground Floor:**
 - Exposure: Exposed To Ambient Conditions | Cap & Finish: 1.25 in. LW Conc | Carpet (no pad)
 - Construction: 2 in. plywood/underlayment
 - Ext/Cav Insul.: - no batt -
 - Interior Insul.: 2 in. polyisocyanurate (R-14)

At the bottom, there is a section for "Infiltration (Shell Tightness)" with values: Perim: 0.038 CFM/ft2 (ext wall area) | Core: 0.001 CFM/ft2 (floor area).

Figure 17: The construction of the building envelope involved the input of R-values and specific building materials.

Beyond the building materials, the different electric loads have the greatest overall impact on the system. The task lighting load was determined by multiplying the five (used) rows of lights by the eight sets of lights in each row by the wattage of each light. Then it is multiplied by the hours of usage per 24-hour period. Ultimately divided by the interior square footage of 154.6 ft².

$$Task Lt = \frac{(5 \text{ rows} * 8 \text{ lights}) * 58 W * \frac{18hrs}{24hrs}}{154.6 sqft} = 11.25 \frac{w}{sqft} \quad (8)$$

The Square footage has been adjusted from 257 ft² to 154.6 because the shelves, pumps, and water storage take up a large fraction of the interior of the unit.

Within the system there are a lot of additional electric loads beyond lighting. These loads generally fall underneath the electric load profile. The load profiles for the large fans, small fans and aerator are 82, 20, and 30 watts. respectively. To find the load per ft², the power of each of the small fans is added to the power use of the large fans and of the aerator. All the values are then multiplied by their usage per day. This value is one since they are constantly being run. Finally, the load is divided by the same square footage used in equation 8.

$$Misc. Load = \frac{[(12 * 20W) + (4 * 82W) + 2.5W + 30W] * \frac{24hrs}{24hrs}}{154.6 sqft} = 3.89 \frac{w}{sqft} \quad (9)$$

One additional load input to the model was that for the pump. The value of the pump load was a lot lower than previous lades because of its hours of operation. Although drawing a large amount of power, 257 watts, the pump was used only twice a day for 20 minutes per use. The equation for the pumps load per ft² was simpler than the previous two. Its base load only had to be multiplied by daily usage and divided by the total adjusted square feet of the building.

$$\frac{257w * \frac{0.66 hrs}{24 hrs}}{154.6} = 0.05 \frac{w}{sqft} \quad (10)$$

Once all energy loads were input correctly, the HVAC system had to be input. Inputs for the HVAC system include determining system type, flow temperatures, and specifics about cooling and heating size and efficiency. Since our model utilizes a mini-split system there is only one machine in out HVAC system. Due to this, most of the inputs were taken directly off the label of our mini-split machine. The system cooling size of 2 refrigerant tons, SEER efficiency of 15, and COP value were all taken directly off the unit label and input to eQUEST®

Figure 18: The important inputs which determine the efficiency of the HVAC system.

After the HVAC system's inputs have been entered, the Building Creation Wizard is done. Which means that the model is ready to be ran. The "Simulate Building Performance" Button was clicked, and eQUEST® began retrieving weather data, and running an analysis of the building

performance. By clicking the “view summary/reports button, the Monthly Energy Consumption by End-use report appears. This report is crucial for comparing the model to actual utility data.

5.4 Results & Analysis

5.4.1 Model Validation

The simulation ran successfully, and even before the utility data was known, the results appeared to be on the correct magnitude. However, to validate the model, a percent difference of less than 10 percent would be necessary with a preferred difference of five percent. An even more ideal situation would be to have multiple years of data from the actual system, but due to the relative new creation of the system, this was not possible. eQUEST®, on the other hand, could produce multiple years of data. Although, the only important year, as pictured in **Figure 19**, is from 2017.

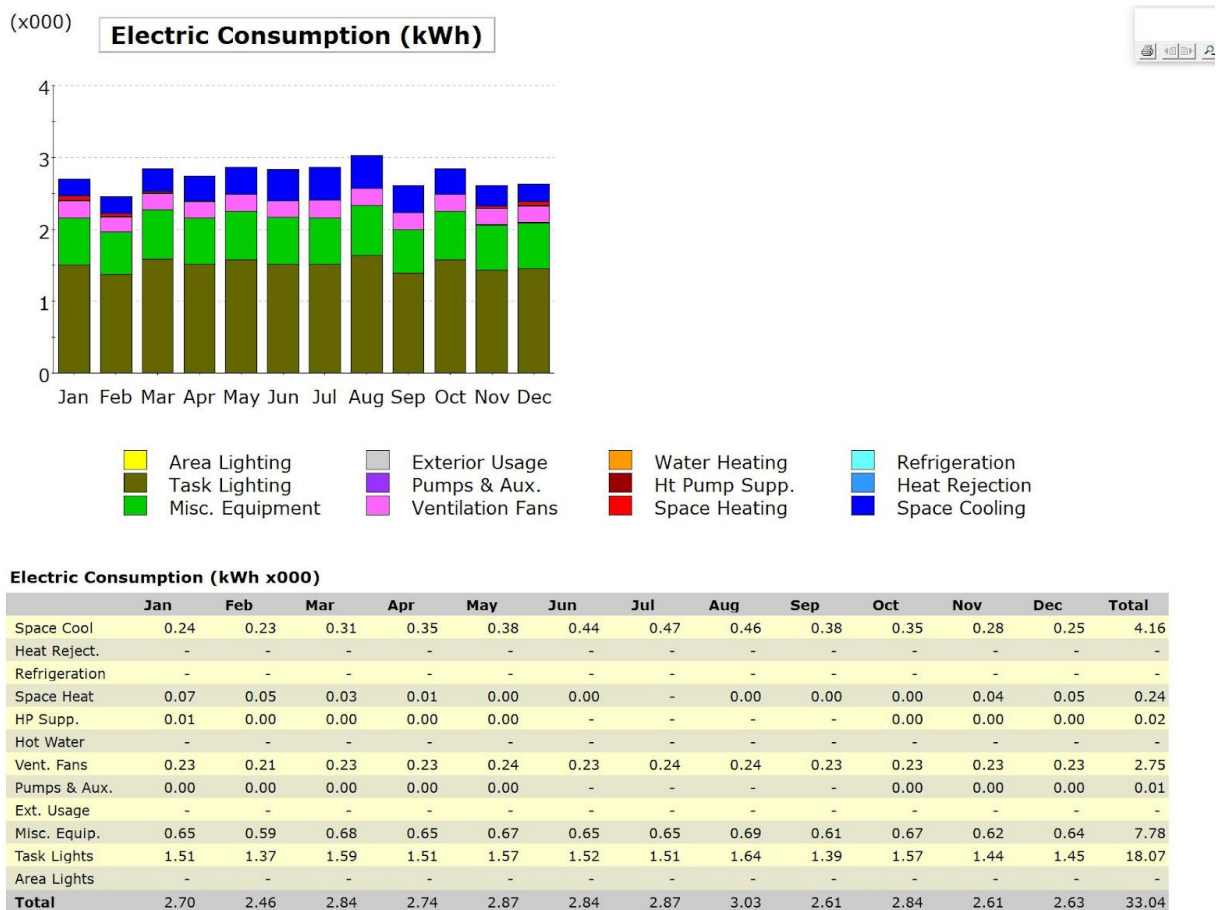


Figure 19: The load profile of the eQUEST® model for the year 2017.

Figure 20 is the Monthly Energy Consumption by End-use report. Even though, the breakdown of each load is important for later analysis, the “Total” row is the important data for validating the model. It will be compared to the monthly utility data provided by Dominion which only shows the kWh’s recorded per month from the systems meter. Monthly metering begins in January of 2017 but the system does not become fully operational until April.



Past Billing, Payment, & Usage

Dominion Energy Virginia

Account Name(s): CALDEJON
RANDY I

Account Number: 4179224292

Service Address: 6577 JARMANS GAP RD
CROZET, VA 22932

Current Date: 2/20/2018

Usage Statement

Meter Read Date	Days	Meter Reading Method	Meter Read	Usage (kWh)	Demand	Avg. Daily Usage
01/31/2018	29		30092	2303	0	79
01/02/2018	32		27789	2575	0	80
12/01/2017	32		25214	2601	0	81
10/30/2017	31		22613	2699	0	87
09/29/2017	30		19914	2713	0	90
08/30/2017	29		17201	2735	0	94
08/01/2017	32		14466	4053	0	127
06/30/2017	29		10413	3186	0	110
06/01/2017	30		7227	3125	0	104
05/02/2017	32		4102	2932	0	92
03/31/2017	29		1170	1170	0	40
03/02/2017	29		0	0	0	0
02/01/2017	29		4345	1	0	0
Totals				30093.0		

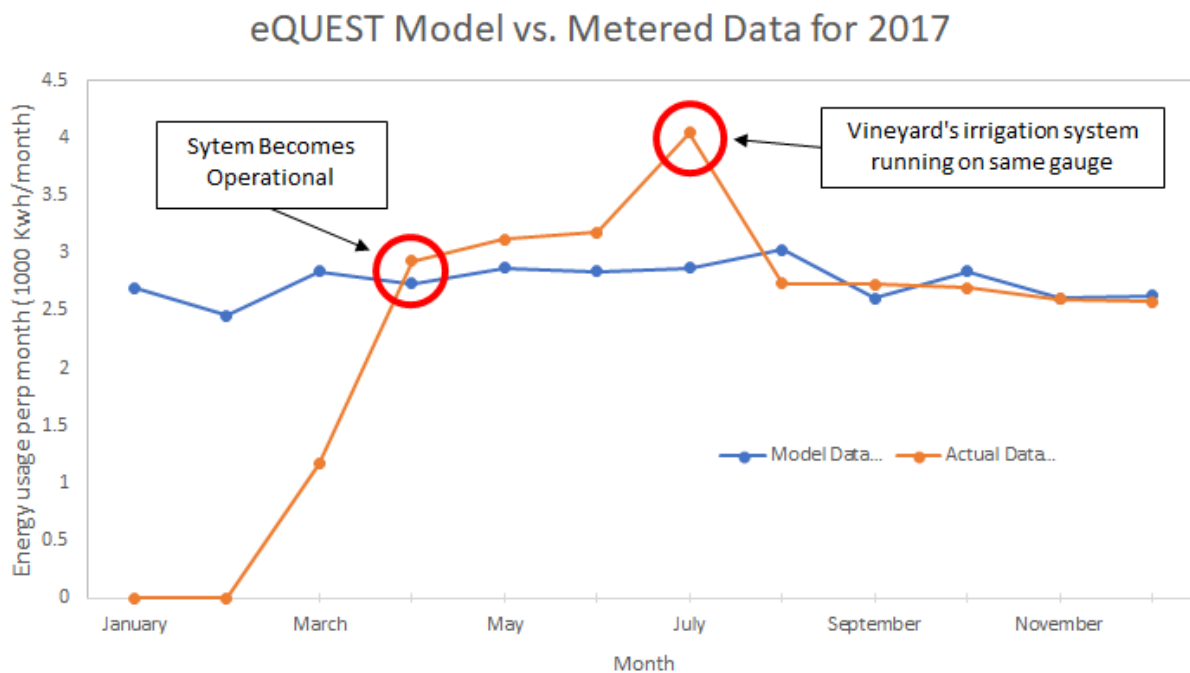
Figure 20: The actual utility bill provided by Dominion energy on February 20th, 2017.

“Usage (kWh)” is the most important column in the utility data. It is what will later be compared to the modeled “Total” monthly data from 2017. Both the modeled eQUEST® data and the metered utility data were plugged into excel and compared to one another. The focus of the comparison was to analyze the percent difference. To calculate percent difference, one subtracts the modeled data from the actual data then divides it by the actual data. The resulting decimal is then multiplied by 100 to create a percentage.

Table 4: Modeled versus actual utility data of the hydroponic system.

Modeled vs. Actual energy usage Data for 2017			
	Model Data (MWh)	Actual Data (MWh)	Percent Error
January	2.7	n/a	n/a
February	2.46	n/a	n/a
March	2.84	1.17	-143%
April	2.74	2.93	7%
May	2.87	3.13	8%
June	2.84	3.19	11%
July	2.87	4.05	29%
August	3.03	2.74	-11%
September	2.61	2.73	4%
October	2.84	2.70	-5%
November	2.61	2.60	0%
December	2.63	2.58	-2%

From **Table 4**, a graph could be made to better visibly represent the data. It is important to recognize that different events had impacts on the “Actual Data.” Such as a nonoperational model until April, and the pumps for the irrigation for the vineyard running during June and July. This can be seen below in **Graph 3**.

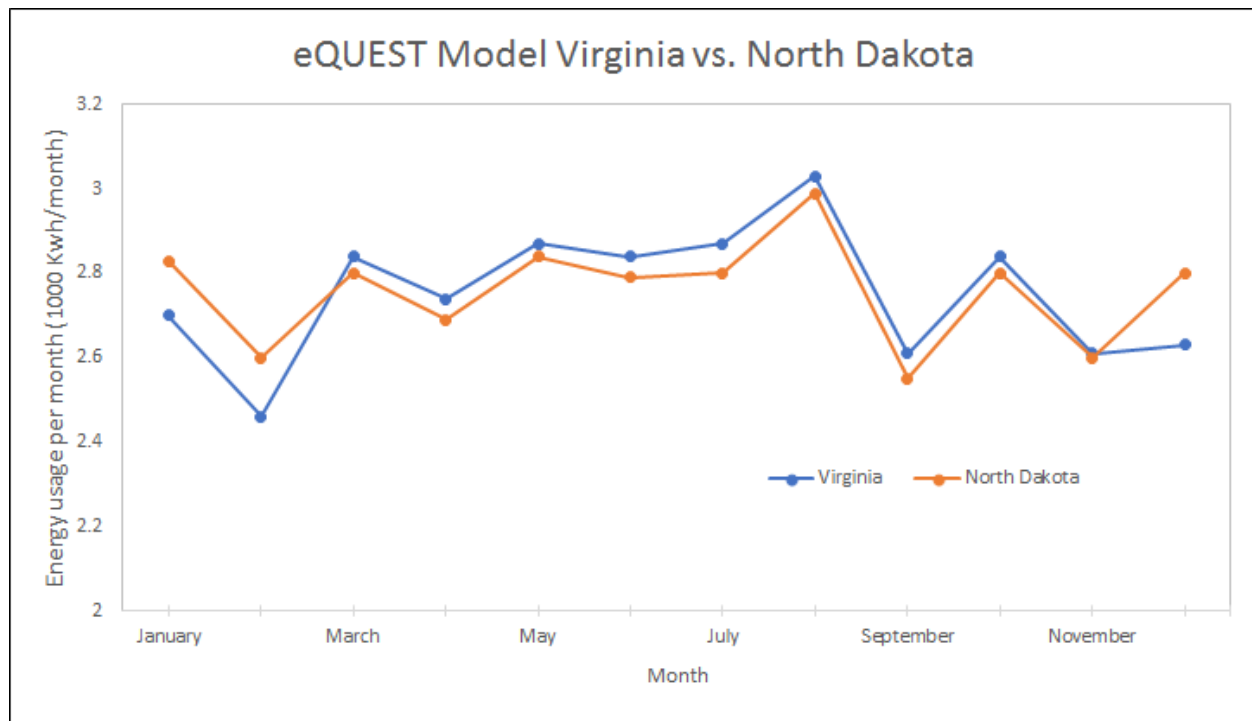


Graph 3: A chart of modeled eQUEST® data compared to actual utility data for 2017.

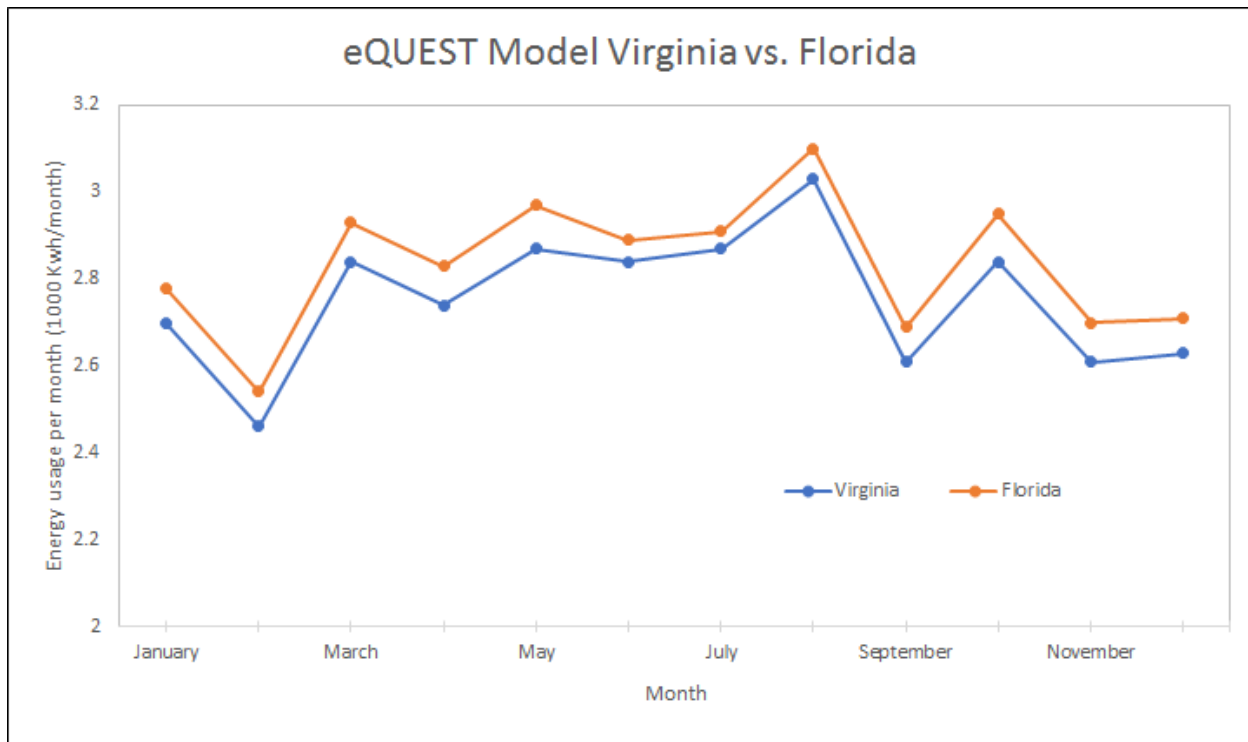
Another goal of this project was to simulate the energy model in different climates. The two places selected for simulation were, North Dakota and Miami, Florida. North Dakota generally offers cooler temperatures than Virginia and has a relatively robust wind resource. Miami, Florida typically has warmer temperatures year-round than Virginia and has a great solar resource. While renewables were not investigated in depth for this project, they were kept in mind when determining a location to simulate for future work.

The model inputs were kept the same for each new location simulation. The only change that was made was to the location, which impacts the weather file that eQUEST® uses for its simulation.

The results of the North Dakota and Florida simulations were compared to the results from the Virginia simulation and placed into Excel®. The generated Excel® graphs can be found in **Graph 4** and **Graph 5**, respectively.



Graph 4: The graph above shows the monthly energy consumption simulated in eQUEST® for North Dakota and Virginia.



Graph 5: The graph above shows the monthly energy consumption simulated in eQUEST® for Miami, Florida and Virginia.

The total annual energy consumption for each state can be found in **Table 5**.

Table 5: The table below shows the annual energy consumption in MWh simulated in eQUEST for Virginia, North Dakota, and Florida.

Location	Annual Energy Consumption (MWh)
Virginia	33.04
North Dakota	33.09
Florida	34.00

5.5 Honors Addition: Efficiency Analysis

One of the many features in eQUEST® is an Energy Efficiency Measure (EEM) Wizard. This tool allows for energy efficiency and payback analyses by changing measurement categories. Category options include building envelope, internal loads, HVAC system, chilled water system, hot water system, domestic hot water, and whole building site. While our system does not deal with any of the water systems, these options are still available for analysis in the EEM Wizard. Once a category option is chosen, a measurement type is specified. Each category has a specific set of measurement types that may be chosen.

The model showed the greatest energy load was from task lighting, as shown in **Figure 19**. The task lighting output values for this model are the lights that are necessary for microgreen growth. An in-depth analysis of this grow lighting was already completed and cannot be modified for

production optimization. Another significant load came from the HVAC system, specifically cooling. The task lighting provided so much heat for the container, that the model shows heating was not necessary for any month. As a result, the following analyses were run for a decreased insulation value, an increased SEER and COP for the HVAC system, and a combination of the two.

Figure 21 below shows the first screen the user encounters when the EEM Wizard is clicked on in eQUEST®. The measurement category selected was the building envelope and the measurement type is the exterior wall insulation.

The screenshot shows the 'eQUEST Energy Efficiency Measures (EEM) Wizard' window. The 'EEM Run Information' section on the left includes a list of measures where 'Ext Wall Insul EEM' is selected. Below the list are 'Create Run' and 'Delete Run' buttons. Further down is a 'Baseline Run Name' field containing 'Baseline Design' and a 'Project & Baseline Run LCC Data...' button. The right side of the window features input fields for 'EEM Run Name' (set to 'Ext Wall Insul EEM'), 'Measure Category' (set to 'Building Envelope'), and 'Measure Type' (set to 'Exterior Wall Insulation'). Below these is an 'EEM Run Summary' section with a text box containing instructions: '*** Press 'EEM Run Details' button ***' and '*** to describe measure ***'. At the bottom right of this section are 'EEM Run Details...' and 'EEM Run LCC Data...' buttons. The bottom of the window has 'Help', 'Finish', and a close button.

Figure 21: The figure above shows the first screen option when the EEM wizard is chosen. The user can specify the measurement category and the measurement type.

Once the measurement category and measurement type have been selected. The input values for the measurement type can be altered by clicking “EEM Run Details...”. Once this has been clicked, the user will encounter a second screen that is specific to each measurement type. **Figure 22** below shows the EEM Run Details for the Exterior Wall Insulation.

The screenshot shows a software window titled "Energy Efficiency Measure Details". Inside, there is a section titled "Exterior Wall Insulation EEM Details". This section contains a table with three columns: "EEM Run Name:", "Baseline Design", and "Ext Wall Insul EEM". The table lists four categories: Construction, Exterior Insul, Additional Insul, and Interior Insul. Each category has a value in the "Baseline Design" column and a corresponding dropdown menu in the "Ext Wall Insul EEM" column. The "Construction" dropdown is currently set to "Metal Frame, 2x6, 24 in. o.c.". The "Exterior Insul" dropdown is set to "1/2in. fiber bd sheathing (R-1.3)". The "Additional Insul" dropdown is set to "- no batt -". The "Interior Insul" dropdown is set to "- no board insulation -". At the bottom of the window, there are buttons for "Help", "Done", and a gear icon.

EEM Run Name:	Baseline Design	Ext Wall Insul EEM
Construction:	Metal Frame, 2x6, 24 in. o.c.	Metal Frame, 2x6, 24 in. o.c.
Exterior Insul:	3/4in. fiber bd sheathing (R-2)	1/2in. fiber bd sheathing (R-1.3)
Additional Insul:	- no batt -	- no batt -
Interior Insul:	1 in. polyisocyanurate (R-7)	- no board insulation -

Figure 22: The figure above shows the first screen option when the EEM wizard is chosen. The user can specify the measurement category and the measurement type.

The baseline design included a metal frame which cannot be altered due to the nature of the shipping container design. The exterior insulation was reduced and the interior insulation was completely removed.

These steps were repeated for the EEM Wizard analysis of an improved HVAC system and the combination of removed insulation with improved HVAC performance. The HVAC system was updated from a SEER of 15.00 and a COP of 2.88 to a SEER of 17.00 and a COP of 4.00.

The results from each trial showed a decrease in energy consumption from the baseline design as shown in **Figure 23**.

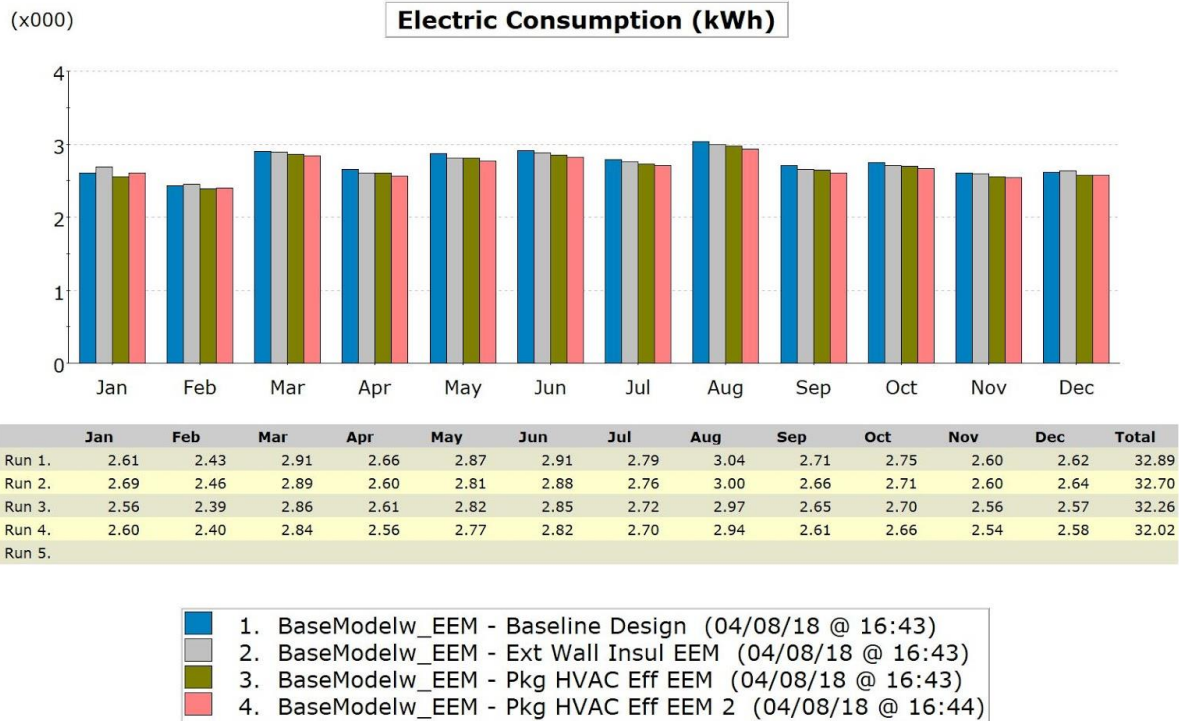


Figure 23: The figure above shows the comparative results from the EEM wizard for each updated component. The blue run number 1 shows the baseline design, the grey run number 2 shows the decrease in insulation design, the green run number 3 shows the baseline design with an improved HVAC design, and the pink run number 4 shows the reduced insulation in combination with an improved HVAC design.

6 Discussion

The model data closely follows the utility energy usage data. The system did not become fully operational until April 2017. This accounts for a lack of data for the months of January, February, and March in 2017. In July 2017, the irrigation system for Fidelis Farms was also hooked up to the Fidelis Greens Hydroponic system. This created a peak in the July 2017 data that does not match the model. However, since the realization about the irrigation was made, this peak in data is expected. The model finds total energy consumption based on a typical meteorological year for weather data. While these values do give good approximations, they do not always reflect extreme or record values that may occur in the year. The slight variation from the model and the real-time data is to be expected because of this weather difference.

Since all internal loads were kept the same for each simulation in Virginia, North Dakota, and Florida, the only energy load that would vary is the HVAC system. A majority of the cooling needs comes from the excessive heat produced from the lighting system in place. The general colder temperatures in North Dakota create a curve that has lower cooling needs in the summer, but higher heating needs in the winter. The general warmer air temperatures and intense solar radiation in Miami increased cooling loads for every month but gave a similar curve shape. A preliminary feasibility assessment of the model in Florida and North Dakota being powered from renewables

was also completed. Florida would utilize its robust solar resource to generate electricity through photovoltaic panels, while North Dakota would rely on its valuable wind resource to generate electricity through wind turbines. A minimum 30 kW solar array is required to provide the minimum monthly energy usage in Florida. A minimum 11 kW wind turbine is required to provide the minimum monthly energy usage in North Dakota. These systems must be used in conjunction with battery storage due to the resources intermittent nature.

The EEM Wizard showed the greatest decrease in energy consumption with a combination of decreased insulation and improved HVAC system. While this decrease in overall electrical consumption is positive, the financial cost of a new HVAC system with a higher efficiency may outweigh its electricity savings. The improved HVAC alone also showed a decrease in energy consumption, but the financial cost may make this option not feasible. Reducing the overall insulation R-value by completely removing the spray foam insulation also decreased energy consumption. By removing the insulation, heat generated by the task lighting can flow out of the container, which reduces the cooling load. While space heating does increase for cooler months, the overall energy consumption still decreases. There is also no added cost for this change, money is saved because insulation does not have to be purchased or applied. Removing the insulation for future iterations is currently the most viable option.

Sources of error may include the square footage adjustment for the model simulation since task lighting can only be entered into the model as Watts/ft². This adjustment was equal to roughly 100 ft² and was made to remove space that was taken by shelving units, pump, and water storage. This was done because these areas do not need the task lighting, but area still part of the model. Calibration of the equipment used to quantify the R-value for each container component may also contribute to uncertainty. The insulation was used to determine heat transfer rates and the resulting HVAC loads. Any error in this measurement will have a moderate impact on the energy use for this measurement category. Our model was also validated with a few months of data. A full year or multiple years of data collection will offer a more justifiable test to the validity of the model.

7 Conclusion

The purpose of this project was to create an energy model that can be used to evaluate energy usage for a hydroponic system in multiple locations. Measurements concerning the input values for multiple components were taken to build the energy model of the hydroponic system. This model was then compared to real-time data collected by Fidelis Greens. The validated model was used to analyze design elements suitable for efficiency increases and estimate energy use in various climates. A model of Fidelis Greens grow box was created and validated with real-time data, allowing for our hypothesis to be accepted. This model can now be used to predict energy use in different climates. The current version of the box in Crozet, VA would be more energy efficient if the insulation was not installed and the HVAC system had a higher SEER and COP due to the heat generation from the growing lights. The combination of these two factors could save approximately 800 kWh for an entire year. While this energy model has allowed for analysis of our current system, there are future opportunities that will further current research. The end goal for future iterations of this system is an off-the-grid version that can be deployed in military applications, urban developments, and disaster relief locations. Future work with this model includes siting for renewables, evaluation of energy storage options, and creation of an improved version of the system. A version of this system and its model may also be brought to JMU to be

used as a teaching tool. The research done in this project will allow for further analysis of new agricultural practices. As climate change impacts water and land availability, agricultural production, and global temperatures, people must find new ways to adapt. Closed-system hydroponics that completely rely on renewables will contribute to food production in the future.

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